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THE USE OF MAN IN BOOSTER GUIDANCE AND CONTROL

by F. A. Muckler and R. W. Obermayer

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MARTIN COMPANY
Baltimore, Maryland
for

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TABLE OF CONTENTS

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SUMMARY

N64-24830

The manned booster guidance and control literature is reviewed and analyzed with regard to basic guidance and control objectives. The present literature strongly suggests that pilot-booster performance will be a function of: the pilot's position in the control loop; the degree of vehicle perturbations and the stability of the booster configuration; the nature of the information displayed to the pilot; the effect of additional task loading on the pilot; and the effects of environmental events occurring during boost. An evaluation of manned booster guidance and control is made on the basis of five criteria: stability; response efficiency; reliability; adaptability; and acceptability.

AUTHOR

I. INTRODUCTION

A. Statement of the Problem

A current design problem of considerable controversy is the use of man as a guidance and control element in large space booster operation. Expert opinion on this problem ranges over the total conceivable spectrum: from fully automatic to exclusively manual control. The automatic control viewpoint is usually held by missile guidance and control specialists with little or no experience with manual control systems. The manual control viewpoint is usually stressed by pilots and/or aircraft control specialists with little or no experience with anything but manual control.

Because all present and projected large space boosters include automatic guidance and control systems as the basic design approach, it may be wondered why there should be interest in redesign for pilot control. The major reason is a concern for booster reliability for man-rated space vehicles. Composite reliability for past booster systems suggest a peaking in the range of 80 to 85% (ref. 1); values that are insufficient for man-rated boosters. The question has been raised as to the potential contribution of the pilot to increasing booster reliability. This contribution could be made in several of the booster subsystems, but because many of the past failures have been attributed to the guidance and control system it may be here that man can make his most significant contribution.

A second problem area concerns abort and booster recovery. At present, the pilot may elect to abort, but he is then committed to free-fall and parachute recovery. With ballistic vehicle configurations and limited controllable propulsion, this technique would appear to be the simplest and most reliable. However, advanced vehicles, and particularly recoverable booster concepts, suggest the use of the pilot as a guidance and control element. One curious line of logic in this context is the following: (1) an automatic system is necessary for normal booster operations since (it is stated) the pilot cannot perform as well as the automatic system, but (2) if an emergency occurs, the pilot will assume direct control. It is not immediately apparent how the pilot can be expected to control far more severe emergency conditions if he cannot control "normal" flight.

A third problem area concerns the actual ability of the pilot to control booster flight, and specifically his comparative ability with respect to automatic booster guidance and control systems. The question has been raised as to whether or not the pilot may indeed be a more precise controller. The ultimate objective of booster operations for manned space vehicles is exact orbital insertion. Acceptable limits for altitude, velocity, and geographical position are very narrow for most applications, and it is possible that the pilot can contribute to precision booster flight.

B. Purpose of the Present Report

These, and other major problems, have been raised with respect to current and projected large space booster operations for manned space vehicles. The purpose of the present report is to assess the currently available research data on the use of the pilot in booster guidance and control. All of these data are derived from ground-based booster simulation studies.

If simulation data are accepted as adequate for design purposes, the present literature suggests a number of direct inferences if man is to be considered in future booster guidance and control systems. It is not, however, simply a question of whether or not the pilot can fly the booster. The simulation data strongly suggest that pilot booster performance will be a function of the interactions of several key subsystem variables, for example: (1) the pilot's position in the control loop; (2) the degree of anticipated vehicle perturbations and the inherent stability or instability of the booster configuration; (3) the specific nature of the information displayed to the pilot; (4) the effect of additional task loading on the pilot; and (5) the effects of potentially adverse environmental events occurring during boost.

C. Criteria for Evaluation

To evaluate the concept of piloted booster guidance and control, and particularly for comparison with automatic systems, a set of evaluation criteria are required. Based in part on the approach of Schmitt (ref. 2) and our own approach to system performance measurement in guidance and control (refs. 3 and 4) five basic criteria of control system performance may be stated: stability, response efficiency, reliability, adaptability, and acceptability. For design purposes, it is essential that precise information be available on all these criteria before final design hardware is selected.

1. Stability. A classic measure of control system performance is stability. It is assumed that if the control configuration does not provide satisfactory static and dynamic vehicle stability, the system is inadequate. This is a critical problem in booster design since a variety of nonlinear phenomena may produce serious, or catastrophic instabilities. A measure of pilot performance is the degree to which he reduces, or creates, vehicular instability.

2. Response efficiency. Booster flight requires usually a short-term although highly precise trajectory with sharply restricted terminal, or burnout, conditions. The nominal trajectory with desired orbital injection values can be stated with theoretical precision. Nonnominal and/or abort operations are more difficult to define. Any booster guidance and control system (manned, semiautomatic, or automatic) can be evaluated with respect to final flight precision. Abort performance is also an indicant of response efficiency in this context.

3. Reliability. As noted, a major reason for considering manned booster guidance and control is the potential contribution man might make to total booster guidance and control reliability. The question is, is man more reliable, as reliable, or less reliable than automatic guidance and control systems?

4. Adaptability. In a direct sense, man is, in many cases, an ideal adaptive controller. His ability to react effectively to unexpected flight conditions may be an attribute desirable to booster control. At least three aspects might be considered: (1) he may be able to perform more precise trajectory flights through his adaptive characteristics; (2) he may provide unplanned vernier control to smooth automatic system performance; and (3) he may be able to perform nonnominal or abort or recovery flights more satisfactorily than a restricted automatic system.

5. Acceptability. With any manual guidance and control system, the traditional practice has been to add a rather unique criterion of pilot acceptance. To be acceptable, the particular configuration must exhibit satisfactory "handling qualities." This concept is difficult to define precisely, but, in general, refers to a set of judgments by the pilot as to which specific guidance and control characteristics can be flown satisfactorily (refs. 5 and 6).

To evaluate the concept of the use of the pilot in booster guidance and control, it is felt that some set of criteria will be useful in reviewing the current literature, in suggesting hardware design approaches, and in deciding about future research programs, if any, in this area. These five criteria, although arbitrary, appear to cover most of the major questions and problems that have been raised to date. Unfortunately, a great deal of the past and present discussions of manned booster guidance and control have been clouded by the emotional content of the discussion. It is hoped that with these five general criteria in mind it may be possible to reach an objective evaluation (at least qualitative, if not quantitative) and comparison of the design concepts of manual, semiautomatic, and automatic booster guidance and control systems.

II. BOOSTER GUIDANCE AND CONTROL: BASIC CONCEPTS

A. Guidance and Control Objectives

1. The nominal trajectory. The statement of guidance and control objectives for man-rated booster flight with reference to terminal conditions is a relatively simple matter. Specifically, the problem is one of arriving at a certain altitude, a specific velocity, and a desired geographical coordinate with an intact vehicle. The selection of these values is, in turn, based on desired subsequent

orbital or escape vehicle operations. Given, therefore, desired terminal altitude, velocity, and position, a nominal boost trajectory can be stated with precision.

The trajectory computed on the basis of terminal conditions must be a non-trivial solution accounting for vehicle thrust limitations, structural limitations, and restraints imposed by the payload and other contents, including human occupants. The control requirements are thus translatable to the maintenance of a nominal trajectory while simultaneously ensuring that suitable considerations are made of the nature and safety of the vehicle and cargo. One can then further specify a host of requirements relating to sequencing and staging, accelerations, body rates, vibrations, noise, etc.

<u>2. Levels of measurement</u>. Based on the above, guidance and control objectives may be specified on three levels: (1) minimum safe performance (2) complete fulfillment of mission objectives (3) satisfactory trajectory control. First consideration must be given to safe vehicle operation, for a control system which attempts to obtain desired terminal conditions in a manner which destroys the vehicle, is, of course, absurd. If safe vehicle operation is assured, then one may, if it seems necessary, try to achieve terminal conditions in any manner whatsoever. Lastly, considerations of precision and reliability will dictate that terminal conditions be brought about in a very particular manner, by following quite closely a nominal trajectory. These guidance and control objectives are reflected in the measurements which one would take in attempting a thorough evaluation, for example:

Level A Safe vehicle operation

1. Vehicle stability
2. Maintenance of safe structural limits (body rate, temperature, etc.)
3. Fuel consumed
4. g
5. Time available for abort operations

Level B Terminal conditions

1. Range, altitude
2. Velocity
3. Attitude

Level C Trajectory measurement
1. Thrust versus altitude, range
2. Staging
3. Subsystem performance (e.g., human operator performance)

It is assumed in this paper that these objectives are valid, and hold for any guidance and control system, manned or unmanned.

B. Guidance and Control Modes

1. Automatic modes. Automatic guidance and control systems have achieved such a good measure of success that every existing booster and virtually every projected booster has an automatic system. The booster and automatic control system are designed together, with mutual tradeoffs made, so that it is essentially unthinkable or, at least, undesirable that the automatic system be removed from the booster. While there is no ground to assert that no future booster will be designed with only manual control, it will be assumed here that automatic guidance and control is a fixed booster feature, and that manual control is achieved by inserting the human operator into the automatic system. For the foreseeable future, and pragmatic purposes, it is believed that this approach is sound.

2. Pilot control: insertion points. As an example of pilot insertion into a booster automatic guidance and control system, Fig. 1 shows pilot utilization modes in a study by Muckler, Hookway, and Burke (ref. 7). The simulated guidance and control loop for the booster under study is shown with respect to the pitch axis, but is applicable to roll and yaw as well. Insertion of the pilot was made at three points, shown in Fig. 1, and the same substitutions could also be made for roll and yaw. As this figure is typical for booster guidance and control, it may be stated that there are basically three modes for the utilization of the human pilot for guidance and control.

Total autopilot replacement. This mode is perhaps the closest to the traditional piloting control function. The pilot has essentially direct control over the engine servomechanisms, and therefore the pilot performs vehicle attitude stabilization and guidance steering control. Failure of any element of this system would render guidance and control completely impossible.

Attitude gyro replacement. No feedback loop exists around the pilot in the case of total autopilot replacement. A step toward automation may be made by allowing the autopilot rate damping loop

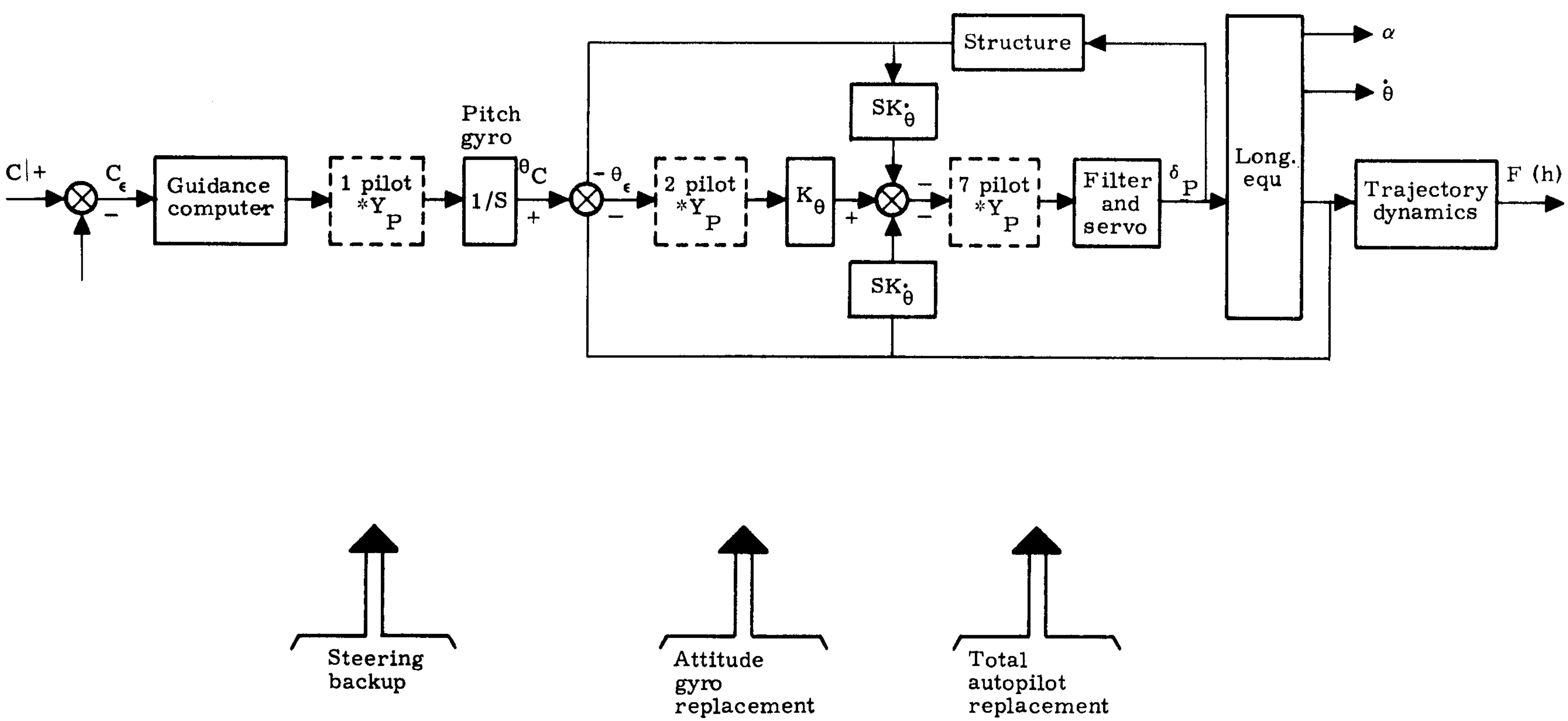


Fig. 1. Pilot Utilization Modes, Pitch

to remain in operation. Past aircraft and booster experience has indicated that damping of this sort may be necessary for pilot control with unstable vehicles.

Steering backup. Perhaps the highest level of automation with continuous pilot participation occurs when the pilot performs steering control (as by applying an output to the torquers that possess the attitude gyros) but the autopilot vehicle attitude stabilization remains in operation.

It will be seen that there are a number of variations possible within each point of insertion for pilot control, and that different choices for pilot insertion may be made for pitch, roll, and yaw axes. Split-axis control, with a number of modes available to the pilot in each axis, is a feasible design philosophy assuming evidence exists that manual control is possible for each of the many available combinations.

3. Ground control. Manual inputs to the booster guidance and control system may be made from ground-based stations as well as from the vehicle crew members. Where the booster guidance and control system contains a command link to ground installation, the insertion of manual commands may be either a primary or override guidance and control function. The Atlas General Electric/Burroughs radio guidance system is perhaps the best known example (ref. 2). With the shift to self-contained inertial systems, ground guidance techniques are not currently in design favor, but, in some cases, they may serve a useful function.

Evidence for this statement comes from a series of studies by Morris and Kaehler (ref. 8) on simulated and actual flights of the X-10 and XSM-64 missiles. Ground operators were given override capability for direct manual control. The results indicated that manual modes of operation were quite satisfactory. Most significant was the fact that 25% of the successful flights "...were saved at some critical control stage by the action of the human control pilot." This action required override of the automatic system, and often the correction of an unstable flight condition.

A second use of ground-based communication links to the pilot is as a supplementary source of information. One pilot booster simulator study (ref. 9) investigated the effect of ground-based data sent to the pilot when the data were not available through the airborne displays, either through display failure or omission. The results were not particularly encouraging, although the problem was not thoroughly investigated. The study did suggest that certain functions (e.g., thrust cutoff) could be better performed through ground command by the pilot. This finding opens the possibility of a ground-based and airborne team operation in performing manual booster guidance and control. At any rate, the usefulness of ground control contributions should not be overlooked. Several functions, particularly those involving extensive computation, may best be performed by ground installations, if time delays are not critical.

4. Abort and recovery. Even in a vehicle with a highly automated guidance and control system, the intervention of man may be desired in the case of catastrophic failure, and/or a means to recover the spent, but still valuable booster.

It may be argued that diagnosis and judgment concerning system failures is man's potentially greatest system attribute, and consequently manually initiated aborts should be made whenever possible. On the other hand catastrophic explosion, for example, may be too fast for human reaction and require a highly reliable, automatic abort system (refs. 10 and 11). Further, a large penalty may be necessary in a manual system to provide the necessary information for the abort decision. However, the use of low-yield explosion, hypergolic fuels may make manual abort systems desirable (ref. 12), if human reaction and decision-making response times are fast enough (refs. 13, 14 and 15).

Paraglider, rigid wing glider, and rigid wing with turbojet have been considered as possible recovery techniques for large boosters (ref. 1). Pilot control of booster flight during recovery is a distinct possibility, but little definition of the tasks involved is available (ref. 16).

On the basis of present information, pilot control during booster recovery may constitute a completely separate set of problems from those of powered launch. In future vehicles, however, pilot control during recovery may become the most critical manual task.

III. PILOT SIMULATOR PERFORMANCE

A. Variables in Pilot Performance

As noted, the accumulated evidence to date consists entirely of ground-based booster simulation studies. From these studies, a number of significant trends have appeared. In general, pilot performance is dependent upon the interactions of several key variables in the guidance and control task: (1) Acceptable performance depends upon the pilot's position in the control loop; his efficiency is quite different if he is providing vernier guidance corrections as compared with three-axis control. (2) The degree of anticipated vehicle perturbations and the inherent stability or instability of the booster directly affect pilot performance levels. Under most cases, stability augmentation appears to be necessary for manual control (ref. 17). Body-axis cross-coupling is a particularly difficult pilot control problem. (3) The specific nature of the information displayed to the pilot and the control devices he uses critically influence his skill. (4) How well the pilot does is determined by the degree of additional task loading he must assume in addition to his guidance and control tasks. (5) Finally, the booster environment is not the most favorable for optimum human performance. The effects of such potentially adverse parameters as acceleration, vibration, and acoustic noise, either singly or in combination, must be considered in predicting operational pilot flight performance.

In the following sections these factors will be considered in turn. A note on the nature of the evidence is in order. For the most part, the studies to date have been primarily feasibility demonstrations. They must be considered exploratory in nature. While they are not characterized by careful design and control they definitely suggest critical parameters for design and future research.

B. Position in Control Loop

As has been noted in a preceding section, the existence of automatic guidance and control systems allows for the insertion of the pilot at several points in the control loop. With this insertion, a spectrum of possible manual control tasks are generated ranging from full manual control to vernier guidance corrections in parallel with the automatic systems. The evidence to date clearly demonstrates that pilot control proficiency changes radically as a function of his position in the control loop.

The initial study (ref. 7) of varying pilot position in the control loop utilized a simulated two-stage booster with pilot insertion points as shown in Fig. 1. The pilot served in one of three utilization modes, either as (1) total autopilot replacement, (2) attitude gyro replacement, or (3) steering backup. In modes (1) and (2) the pilot performed the traditional three-axis, continuous, flight task. The conditions differed only in that mode (2) provided three-axis rate damping while mode (1) did not and was, in fact, direct manual guidance and control. In mode (3) the pilot replaced the guidance computer, and his task was to provide steering control by applying rate signals to torquers that precessed the attitude gyros.

In modes (1) and (2) the pilot provides control signals; in mode (3) he transmits guidance commands.

The objective of this study was to investigate the ability of the pilot to stabilize the booster after it had been perturbed by external inputs. As shown in Table I, four points along the boost profile were studied. Given perturbations to the booster, the pilot had no difficulty stabilizing the booster in the attitude gyro replacement mode (2). In mode (1), however, with the rate damping loop, the pilot could stabilize first stage conditions (aerodynamically stable), but not the second stage (aerodynamically unstable).

Figure 2 shows the kind of catastrophic instability that can be generated with respect to pitch error (θ_e) and pitch rate ($\dot{\theta}$) at both Stage II ignition and Stage II burnout. This result was produced, without exception, for every pilot who flew these conditions.

These results clearly indicated that the pilot's ability to stabilize the booster depended upon his position in the control loop, the particular flight condition, and the inherent stability or instability of the booster dynamics.

C. Perturbations, Booster Flexibility, and Stability

It is apparent that vehicular stability plays an important role in determining pilot manual control performance. The classic study on this point is that of Holleman, Armstrong, and Andrews (ref. 18). Simulated trajectory flights were flown with two- and four-stage boosters, under fixed-base and centrifuge simulation. Vehicle stability and damping were varied over a wide range of values resulting in both stable, well-damped, and unstable, lightly damped, configurations. Their data show clearly many critical pilot control problems are caused by perturbations during staging. As they point out (ref. 18, p 8): "The primary cause of the control problem was vehicle aerodynamic instability, but loss in control thrust, change in vehicle geometry at staging, windshears and burnout moments also contributed to the problem." Further, the greater the delay between thrust cutoff and next stage thrust initiation the less vehicle instability can be tolerated.

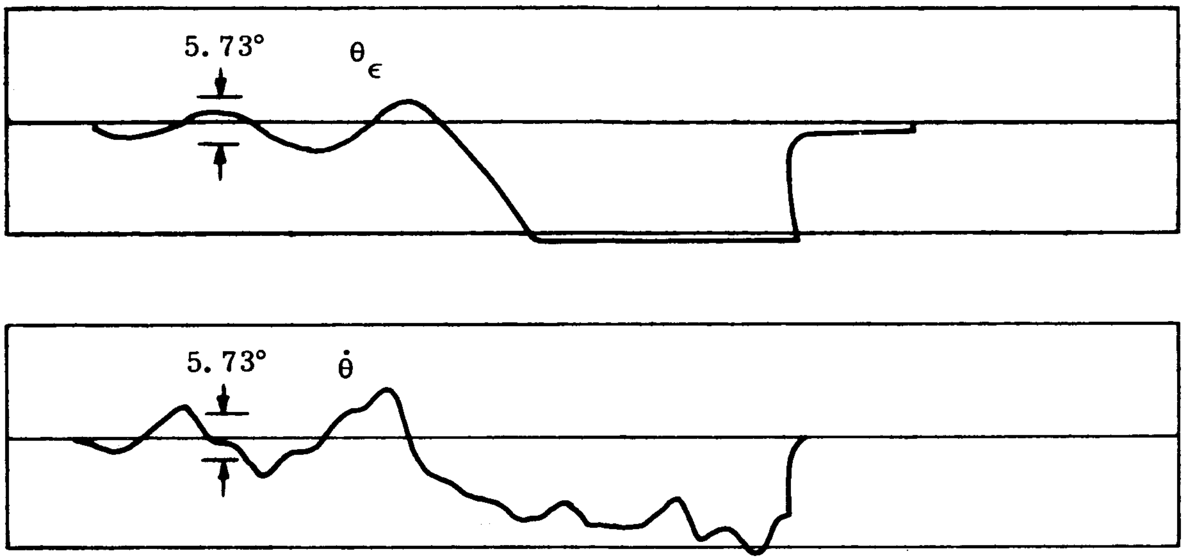
It should be noted boosters are not rigid bodies, but tend in fact, to twist and bend (ref. 2). Structural bending modes, for example, can have a marked effect on pilot control, and Holleman, Armstrong, and Andrews (ref. 18) demonstrate a sharp interaction between structural flexibility, control effectiveness, control limits and vehicle instability. They note (p 9): "A 10-percent loss in control effectiveness due to flexibility resulted in only small changes in the controllability boundaries; however, a 20-percent decrease in control effectiveness resulted in as much as a 50-percent reduction in the amount of instability that could be controlled by the pilot." Several studies in this literature have assumed rigid body dynamics in their simulation; these studies may have produced over-optimistic results with respect to pilot control. Since booster flexibility is a part of the operational vehicle and since Holleman, Armstrong and Andrews (ref. 18) and others (ref. 9) have shown these effects can influence pilot control levels, they must be included in future studies if realistic simulation is to be achieved.

TABLE 1

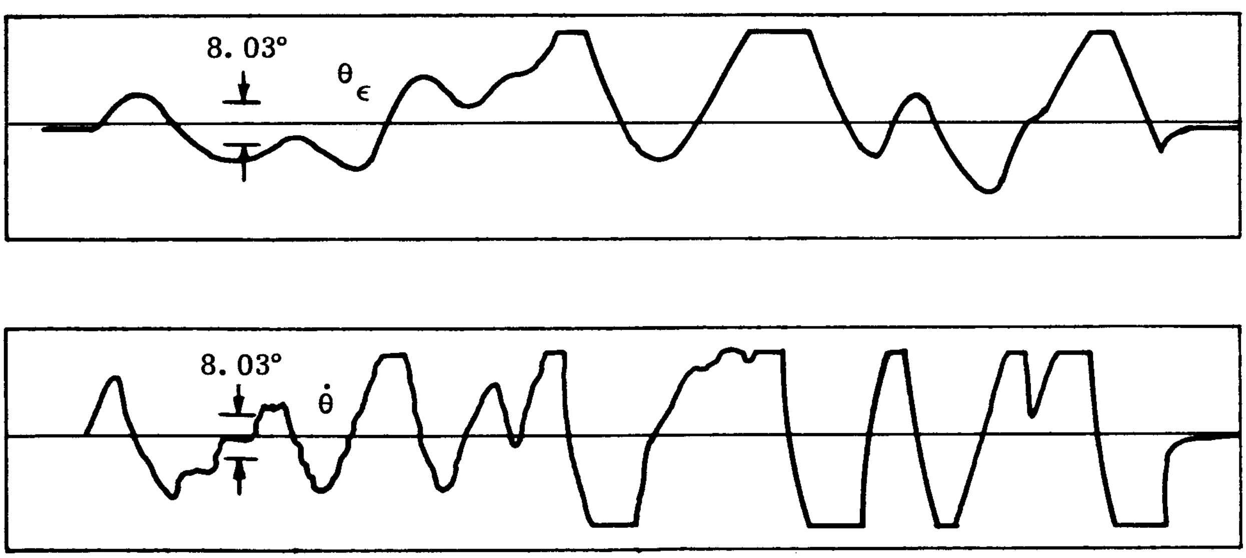
Pilot Stabilization of a Two-Stage Booster (ref. 7)

Boost Stage	Flight Condition	Pilot Control Mode: Total Autopilot Replacement	Pilot Control Mode: Altitude Gyro Replacement
First	Max Q (M=1.5)	Stable	Stable
	100 sec (M=3)	Marginally Stable	Stable
Second	Stage II Ignition	Catastrophic Instability	Stable
	Stage II Burnout	Catastrophic Instability	Stable

One major source of external vehicle perturbation during atmospheric flight is wind shear and gusts. The need for realistic wind profile simulation has been demonstrated with respect to the design of automatic control systems for boosters (ref. 2), and there are data illustrating the same for manual studies. Table 2, for example, shows mean terminal trajectory values derived for a three-stage booster simulation with the wind profile present and absent in the simulation.



a. Pitch axis, Stage II ignition



b. Pitch axis, Stage II burnout

Fig. 2. Catastrophic Instability with Pilot Serving As Total Autopilot Replacement, Second Stage of Two-Stage Booster Simulation, 5° Step Pitch Command Perturbation (Ref. 7)

TABLE 2

Pilot Trajectory Control: Three-Stage Booster (ref. 19)

Pilot Control Mode	Wind Simulation	Mean Terminal Values		
		h_e (ft)	V_e (fps)	h_c (fps)
Attitude Gyro Replacement	No Wind	+4,667	0	-52
	Wind	+32,667	-41.7	+52
Allowable Terminal Tolerances		$\pm$6,400	$\pm$17.7	$\pm$25

Under the no-wind condition, mean pilot performance appears to fall within allowable terminal tolerances for altitude (h_e) and velocity (V_e) suggesting reasonably successful flights. Introduction of the simulated wind profile, however, radically changes the comparison. Pilot terminal performance falls well outside the allowable terminal tolerance limits.

D. Displayed Information and Controller

1. Information requirements and pilot displays. Essential to the selection and design of pilot displays is a statement of the basic information requirements for pilot guidance and control functions. Several categories of information may be identified:

(1) Vehicle attitude
- (1) pitch parameters
  - (a) pitch angle and rate
  - (b) angle of attack
  - (c) flight path angle
- (2) roll error and rate
- (3) yaw error and rate

(2) Position and velocity
- (1) altitude
- (2) range
- (3) velocity

(3) Propulsion
- (1) Thrust
- (2) Staging sequences

(4) Vehicle conditions
    (1) acceleration
    (2) angular body rates

(5) Timing indicators

It does not follow necessarily that all of these parameters must be displayed, and, in fact, the studies in the literature have used a variety of information and display configurations.

In some cases, systematic study has been made in comparing the effectiveness of various display configurations. There is no question that the particular displays markedly affect pilot performance. The proficiency of his performance is directly influenced by the kind and quality of the information he receives. Some of the results found to date may be summarized as follows:

(1) For pitch control, flight-path angle display is superior to pitch angle, but is dependent upon the scale sensitivity. A full-scale sensitivity of $\pm 2^{\circ}$ is excellent; $\pm 1^{\circ}$ is too sensitive (ref. 18).

(2) For pitch control, angle of attack display is superior to pitch angle display (ref. 19).

(3) Pitch, roll, and yaw rate must be displayed as well as pitch, roll, and yaw displacement error (refs. 9 and 19).

(4) For altitude control, gross altitude (total range) and vernier altitude (at staging and insertion) information should be displayed (ref. 9).

(5) Command signals for pitch, roll, and yaw are desirable to show desired pilot performance although pitch is perhaps most important (ref. 19).

(6) An integrated flight path command signal (based on a guidance optimization criterion and including $\ddot{h}$) is superior to separate presentations of command program signals (ref. 9).

(7) A combined presentation of altitude and velocity is insufficient for successful pilot mission completion (ref. 18).

(8) A combined presentation of altitude (h) and rate of climb ($\dot{h}$) is not sufficient for precision pilot control (ref. 9).

(9) A combined presentation of velocity (V) versus altitude (h) and pitch angle (θ) gives acceptable performance, and in turn is superior to altitude (h) and pitch angle (θ) presented separately (ref. 18).

(10) Warning lights to indicate the occurrence of critical staging events are desirable (refs. 9 and 18).

In all studies to date, it is apparent that superior display systems have yet to be developed, and that a great deal of improvement is possible. The vintage 1940 cockpit, with its gross and often inaccurate dials, is clearly inadequate for this extremely sophisticated piloting task. Integrated displays and integrated command guidance command signals are necessary for precision pilot performance at any level of booster control.

2. Controller design. Due primarily to anticipated acceleration effects on the pilot, design of the pilot's controller has emphasized side-located controls as opposed to the conventional center stick. Kaehler (ref. 20) was the first to show that, under varying acceleration loads, a right hand, two-dimensional, control was consistently superior to the conventional center stick. A pilot preference was indicated for the side stick due to the lower forces required to move the side control under acceleration loads. The data also suggest that the use of the side controller is more flexible than the center stick in pilot adaptation to varying or unexpected acceleration loads.

One major problem in the use of a side controller is inadvertent pilot control cross-coupling. Andrews and Holleman (ref. 21) have shown that, as acceleration loads increase, control coordination becomes increasingly difficult and more frequent inadvertent control outputs occur. This finding has been noted in a number of other studies, and in at least one case (ref. 22), required a shift from a three-axis side controller to a two-axis-rudder pedal configuration.

Pilot opinion has varied considerably on the optimum controller configuration. However, the evidence to date clearly indicates that a side-located controller is the design choice. Specific characteristics of the side control (e.g., number of axes, force loadings, gear ratios, pivot points, rotational vectors, etc.) must be determined within the particular application problem, and are probably best adapted to the specific pilot population. One problem that should not be overlooked is the potential effect of personal protective equipment. Andrews and Holleman (ref. 21) reported that pressure suit gloves tended to decrease pilot control efficiency. In general, the data suggest an interaction between type of control, acceleration loads, control characteristics, and personnel equipment factors in determining pilot control efficiency.

E. Task Loading

For the total crew station design, the fact must be taken into account that the pilot may not be able to devote his full time to guidance and control. Communication links must be established and maintained. Careful attention must be given to the operation of the life support equipment; if Project Mercury experience is any indication, this may be a major pilot task.

A significant question, therefore, may be asked: what is the effect on manual guidance and control if the pilot cannot devote his full attention to control? Data on this question are available from one published study (ref. 7).

In this study, the pilot assumed three-axis booster control, and was required only to stabilize the vehicle with the introduction of varying disturbing ramp inputs to pitch alone. To this was added the task of scanning a panel of malfunction detection indicators (MDS-1) and putting out those lights illuminated at random. A further task load was given him by requiring that he scan the detectors, extinguish, and report by voice communication his action (MDS-2). The resultant is shown in **Fig. 3**.

In the wealth of variability shown in these data, several interesting trends appear. As the severity of the external ramp inputs increase, the maximum pitch rate response increases. As should be expected, this has no direct apparent effect on roll (ϕ) and yaw (ψ) rates. The introduction of the two secondary tasks leads to a somewhat complex response. In pitch, with tasks MDS-1 and MDS-2, pitch response actually improves. In roll, the addition of MDS-1 degrades performance somewhat, but with MDS-2 performance compares quite favorably with primary task ("task only") performance. It is in yaw that the secondary tasks show the most marked effect. Yaw control is, at best, poor, and the additional tasks push yaw rates to or beyond the MDS limit - which in the vehicle would mean automatic abort. But the degree of external ramp inputs for pitch plays a part as well. It is only with higher disturbances that the problem becomes critical.

The explanation of these data is reasonably simple. Although the pilot is exerting three-axis control, his primary concern is pitch control - where disturbances are occurring. As his control problems in pitch increase (both through more severe inputs and the addition of secondary tasks), he tends to change his sampling rate to the point where yaw receives relatively little attention - with unfortunate results. It is encouraging, however, that the pilot can maintain adequate two-axis control (pitch and roll) even with severe external disturbances, distracting secondary tasks, and an unstable configuration.

If these findings are valid and generalizable, a design implication is that split-axis control should be examined where, in specific applications, pilot control and/or intervention in one or two axes may be desirable. It also suggests some rather strict restrictions on full three-axis pilot control or override. Under these implications, the pilot becomes supplementary to automatic attitude control, but retains his flexibility to override automatic control if, in his judgment, such action becomes warranted by circumstances. The choice, then, should not be full manual or full automatic, but rather a flexible decision context where selective axis control alternatives may be exercised by the pilot.

F. Environmental Variables

Until recently, it has been widely stated that man has either no function or very limited functions in the boost phase, based on the assumption that the boost environment would be so severe as to preclude efficient human performance. At least three critical environmental variables must be considered both singly and in interaction (1) acceleration loads, (2) vibration, and (3) acoustical noise. These are by no means the only critical environmental variables, but they can be assumed to be most important within the context of the present report.

1. Acceleration loads

Predicted longitudinal acceleration. Table 3 presents theoretical estimates of longitudinal g forces as a function of the time sequence of the boost phase for a hypothetical three-stage booster of the 1965-1970 era.

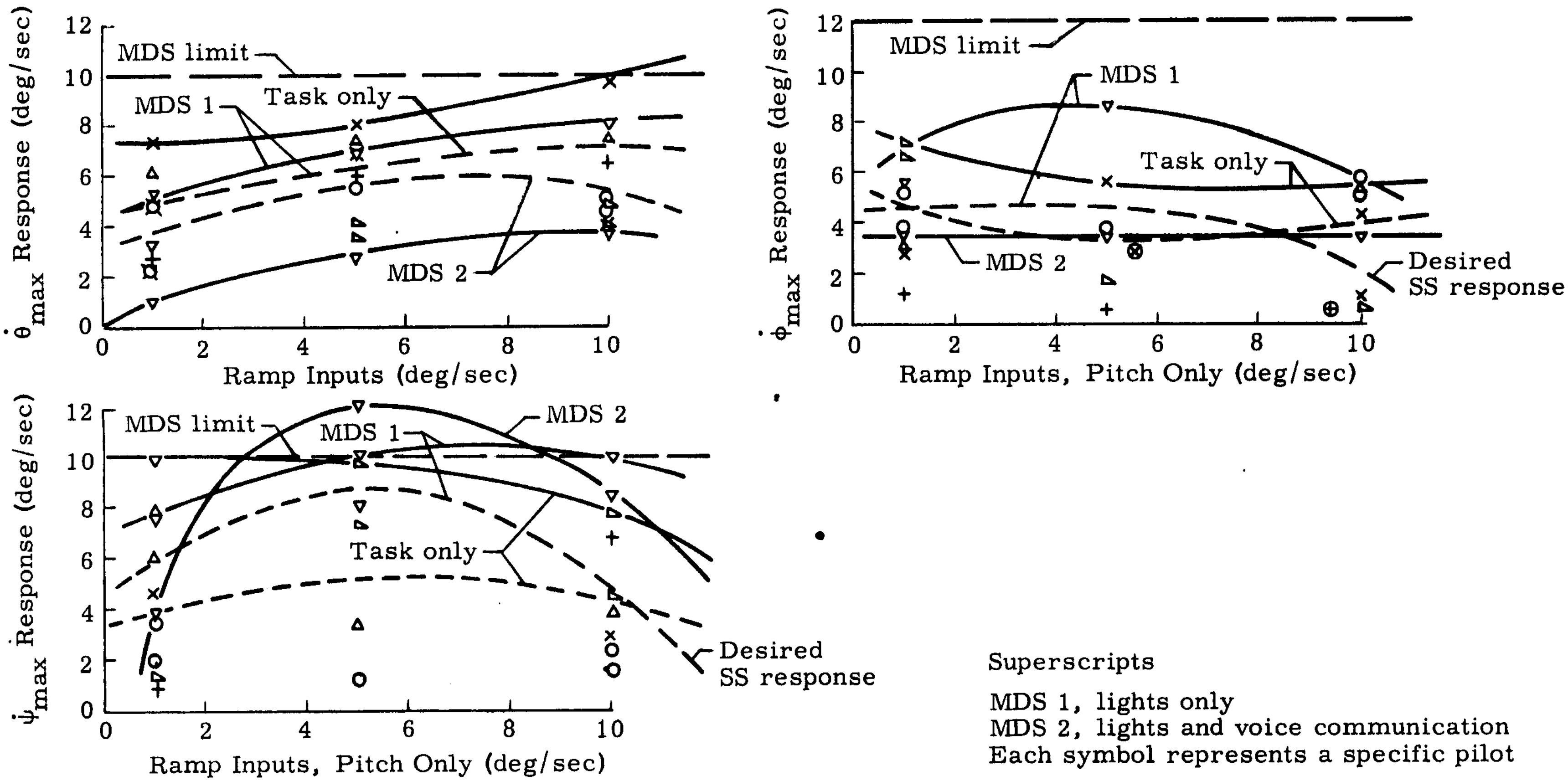


Fig. 3. The Effect of Additional Pilot Tasks on Pilot Booster Control

TABLE 3

Estimated Longitudinal Acceleration (g) Loads: Hypothetical Booster

First Stage		Second Stage		Third Stage	
Time (sec)	g	Time (sec)	g	Time (sec)	g
0		152.32	1.31	503.85	1.58
20		196.32	1.52	535.85	1.61
40		236.32	1.66	575.85	1.65
60	1.27	276.32	1.81	615.85	1.70
80	1.96	316.32	1.97	655.85	1.74
100	2.76	356.32	2.13		
120	3.64	396.32	2.31		
140	4.78	436.32	2.52		
150	5.59	476.32	2.79		
152.32	5.90	503.85	3.02		

These data are gross estimates only, and are expected to point out general trends. It may be noted that the peak g loads are relatively low, certainly considerably lower than high-speed aircraft. The highest g load occurs at the end of the first stage (g = 5.9).

Physiological tolerance limits. It should be understood that the physiological effect of acceleration loads on the human body is a function of several variables. Acceleration level, time of exposure, rate of onset, direction of the force with respect to the body, method of body support and restraint, individual tolerance differences, and so forth, are among those variables that must be taken into account in the prediction of physiological effect. The restraint system, for example, is particularly critical. Clark (ref. 23) has noted that it is not acceleration or deceleration forces that damage man but rather the body distortions that result from an unbalanced action of these forces. Proper restraint can do much to increase human tolerance limits to acceleration loads.

It is assumed that the loads listed in Table 3 will be imposed on the crew in the $+g_X$, or chest-to-back, direction. The data in Table 3, if valid, suggest a reasonably favorable conclusion on the effects of these loads on the crew members. A number of studies in the literature are applicable (refs. 24 and 25), and imply that no physiological tolerance limit would be reached.

Human performance limits. Although no adverse physiological effects may occur, it is possible that human performance could be restricted. Reference has already been made to the studies of Kaehler (ref. 20), and Andrews and Holleman (ref. 21) with respect to controller design. In both cases, some performance decrement was reported under g-loads. The work of Holleman, Armstrong, and Andrews (ref. 18) included staging accelerations of 3, 6, 9, 12 and 15g. Due, possibly, to an excellent support and restraint, there was little performance decrement at up to the levels of 9g. Above 9g, physiological effects were noticeable (e.g., loss of peripheral vision), and pilot performance was markedly degraded.

If the values shown in Table 3, however, are typical of future boosters, pilot performance can be predicted to be essentially undisturbed. A note of caution is in order. While the peak loads and rates of onset shown in Table 3 are not severe, the duration of exposure in some cases (e.g., Table 3, Third Stage) is extensive. Fatigue may become a critical factor in these cases, and, if so, marked performance decrement could occur.

2. Vibration

Human tolerance to vibration. It is apparent that the vibration pattern imposed on man from large boosters will be derived from several possible sources: mechanical vibration of the power plant, rapid changes in acceleration particularly on burnout, acoustical noise, wind shear and gusts, and so forth. Specific vibration levels depend upon the details of engine and vehicle structure, aerodynamic conditions, and the technique of vehicle operation. No generalized analysis of the potential effects of vibration can, therefore, be made. For each application, it is necessary to record a complete time history of lateral accelerations in the low frequency range.

In general, it can be stated that the most serious effects of vibration on man occur in the low frequency ranges. Any frequencies below 20 cps can be a major problem insofar as their effect on crew members is concerned. It might be pointed out that experimental animals have been killed in a few minutes by low frequency vibrations of approximately 10 cps (ref. 23). Further, the gross human body natural frequency as well as that of the heart as it is suspended within the chest cavity lies in the 4-6 cps range.

Booster vibration levels. Each booster presents its own vibration spectrum, and must be individually evaluated. To date, in the Project Mercury program, booster vibration has not presented a problem. However, in larger boosters than Atlas, increasing difficulties may be encountered. However, there are several effective engineering solutions to this problem from the crew standpoint. Adequate restraint, for example, can remarkably improve human vibration tolerance. Vibration is not to be ignored; however, solutions are readily available.

3. Acoustic noise

Physiological and performance limits. In general, a continuous noise level of approximately 120 db (re. 0.0002 mb) will cause distress in the majority of humans while a 130 db level will cause pain. Disorientation, nausea or vomiting can be induced by noise levels in excess of 150 db. To date, critical noise levels have not been a major problem in man-rated booster operation, although the noise levels have not been particularly pleasant. Considerable noise attenuation occurs through the structure, the pressure suits and helmets.

Future boosters. No precise predictions are available in the open literature on future booster noise levels. Simply on the grounds that they will be larger and contain more engines, one might expect higher, and possibly dangerous, noise levels. As was the case with vibration, however, each booster will have to be examined for the specific noise spectrum involved.

4. Summary. A brief examination has been made of the potential effects of acceleration loads, vibration phenomena and acoustic noise levels on pilot and crew performance during boost. With present boosters, the launch environment is by no means an optimum setting for crew performance. For future boosters, it is probable that environmental variables will become increasingly more important. It should also be noted that the crew members will, in fact, experience a combination of these effects with a multi-stress resultant.

Neither the effects of single nor multiple stresses can be predicted at this time. Insufficient information is available on the specific acceleration, vibration and noise values for projected boosters. Once these values are known, there is adequate basic physiological and psychological data for preliminary feasibility estimates of proposed manual guidance and control modes. However, for hardware, extensive simulation tests are mandatory for feasibility demonstrations and, for that matter, as a check on flight safety. The centrifuge studies of the Dyna-Soar booster are an example of this type of testing (refs. 17, 26, 27 and 28).

G. Summary and Comment

In many of the discussions of the feasibility of manual booster control, the assumption is often implicit that there is a clear choice between manual and automatic modes. Either the pilot flies the booster, or the machine flies it. Such a dichotomy is unfortunate, if not useless. Based on the accumulated evidence, and our own experience, a more reasonable and fruitful, approach is to assume that the pilot can make a significant contribution to guidance and control together with the automatic system. The design problem then becomes the detailed specification of what that contribution shall be.

This problem is not easily solved. It is to be hoped that the simulator evidence presented in this section demonstrates: (1) the number of variables that influence pilot performance and (2) the complexity of the interactions that will determine pilot performance. There is no easy design solution. Man is not a fixed component; he is flexible, adaptable, nonlinear, and sometimes to the designer inexplicable. For control design, these attributes are at once highly desirable and undesirable. They are desirable because they are the reason why man is such an adaptive controlling device. They are undesirable because they increase the uncertainty of specific human behavior in a complex guidance and control system.

The evidence to date implies that several key points must be watched in design development. How well the pilot performs depends upon where he is placed in the control loop; the closer the design comes to full manual control, performance variability and response accuracy become critical limiting factors. The pilot has control limits, but we are not sure at this time precisely what these are. The limits must be empirically determined for each application taking into account vehicular instabilities, external disturbances, structural flexibility - in short, all the complex physical phenomena that occur during booster operations. The same variables, in fact, that must be considered in the design of automatic systems. The inclusion of man is not an easy way out.

Clearly, the optimum display of information is a highly unresolved situation. The statement is often made that with "better" displays the pilot will produce better performance. Until a more substantive definition of "better" is available, the statement is true (based on past experience), but not particularly helpful. While the problem of optimum controllers is troublesome, it is relatively insignificant to the problem of improved displays.

A safe, although conservative, design approach is to assume for any application that the pilot cannot be exclusively assigned the task of guidance and control. He may have other duties, and task-sharing will definitely influence his control performance. With multi-man crews, this problem hopefully can be resolved.

Finally, the adverse environment must never be overlooked. The evidence is definite that these variables, in the operational context, will influence pilot performance. One implication is that the predictive validity of results from fixed-base and part-task simulation is possibly reduced. But these test techniques are essential to design, and their use should be increased for more specific empirical checks on the evolving design. The final design (or a small number of alternatives) should then receive proof-testing in the full dynamic environmental context provided by centrifuge and other devices.

IV. THEORETICAL PREDICTIONS OF PILOT PERFORMANCE

The preceding section would suggest that manual booster control system design is a strictly empirical matter. For the most part, this is true, but it would be most desirable to introduce quantitative analytic control system methods into this context. Hopefully, with valid analytic methods, the extensive experimental and test demands for every study of this type could be radically reduced. Attempts have been made to use analytic techniques in only two studies (refs. 7 and 9) one concerned with stability predictions, the other directed toward the generation of an integrated command display signal based on specific flight path optimization criteria.

A. Stability Predictions

An example of stability predictions is provided in the studies reported by Muckler, Hookway, and Burke (ref. 7), previously cited. Due to severe limitations in the predictive techniques, the stability predictions derived were used primarily as a secondary design aid. All conditions were empirically checked in simulation.

A single-plane analysis was used to determine Nyquist Stability predictions for both the total autopilot replacement mode and the attitude gyro replacement mode for eight discrete flight conditions in the total booster trajectory. In order to generate the required open-loop amplitude and phase plots, a mathematical description of human operator transfer characteristics is needed. Since it is difficult to estimate the total influence on booster performance of the nonlinear, time-variable, and adaptive aspects of human control behavior, it would be preferable to have a complete mathematical description of the human operator. However, from a review of the literature, the only model available based on more than scanty development is the linear approximation of McRuer and Krendel (refs. 29 and 30). This transfer function consists of a linear term plus a remnant term which includes all effects incapable of linearization. In order to use conventional servoanalysis techniques, of course, it is necessary to assume that the remnant term is zero, and to employ only the linear approximation of the following form:

$$Y_p = \frac{K_p e^{-T_p S}(T_L S + 1)}{(T_N S + 1)\ (T_I S + 1)}$$

It will be noted that there are five parameters to specify before the transfer function can be utilized, and, unfortunately, even with careful description of the manual control task, only approximate values with high variance can be extracted from the existing literature. The approach in this study was to make repeated analyses with transfer function parameters sampled from the expected range of variations:

K_p : pilot static gain (normalized to unity)

T_p : reaction time delay (0.2 and 0.5 sec.)

T_L : pilot anticipation lead time constant (0 and 2 sec.)

T_N : neuromuscular lag time constant (constant at 0.1 sec.)

T_I : pilot error smoothing lag time constant (0, 0.1, 0.2 sec.)

The transfer functions thus derived were assumed to provide an adequate sample from the spectrum of possible human performance, and subsequently were used in a conventional Nyquist stability analysis.

The results of the Nyquist analysis can be termed highly successful. Upon comparison with fixed-base simulation results it was found that: (1) predicted cases of Nyquist instability were quite unstable, (2) Nyquist-stable conditions were in fact stable, and (3) cases which appeared marginal on examination proved to be quite difficult tasks for the human operator. The findings shown in Table 1 were all predicted by the Nyquist analysis.

Although, on the basis of these results, the Nyquist technique should be recommended for future consideration, the success achieved must be viewed with some measure of skepticism since essentially every assumption required by the Nyquist technique is in opposition to our knowledge of booster manual control systems. The Nyquist method allows a technique for handling the transcendental delay term in the quasi-linear model: however, it is a linear technique. Ascension through the atmosphere, structural bending, fuel slosh, asymmetrical thrust, cross-coupled dynamics create a set of system conditions which stand in sharp contrast to the assumption of linearity. To compound the problem, the human operator displays adaptable, time-variable, nonlinear, and intermittent behavior. Data for the quasilinear model were collected with low-frequency input signals and little or no dynamics in the system. The whole human transfer function concept must be treated with caution for analytic purposes, as, for example, it has no meaning in the open-loop case.

Two avenues for deriving improved stability prediction techniques are through improved human transfer function descriptions and more appropriate stability criteria. There is reason to suppose that improvement is possible since both problem areas are quite active, for example, in developments of sampled-data and ortho-normal filter models of the human operator, Liapunov stability, and a number of other active theoretical developments. However, at the present time, empirical simulation is the only safe method. For design purposes, since simulation is required for purposes other than stability checks, and is available in most designs for stability investigations, possibly a straight empirical approach may be more efficient in design until there is more certainty in the validity of analytic tools.

B. Guidance Command Programs

A number of possibilities exist relative to the types of information displayed to a human operator in control of a man rated booster. First, and perhaps most consistent with aircraft tradition, is that one can simply display vehicle status information: altitude, velocity, attitude, etc. The pilot is then required to provide to the situation all information pertinent to an appropriate path through space, and appropriate control action to produce implied maneuvers. The pilot may be required to arrive at fixed terminal conditions with relatively little constraint on the particular path utilized; however, as with orbital insertion, close approximation to an optimal path is necessary, strongly suggesting the display of nominal path command information. Lastly, given sufficiently precise information about what is happening and what should happen, the pilot may need information to aid in taking proper control action.

If vehicle control requires human responses beyond physical limitations, there is little choice but to remove the human operator as a control element. However, if a control task is difficult due to improper operator control action, a technique termed quickening has shown much promise. Quickening is said to provide the human operator with knowledge of the effect of his responses, usually through the display of derivative information. In one study (ref. 19), pilots were required to fly full pitch trajectories using, in one case, a basic panel presenting actual and command pitch, roll, yaw, velocity, altitude, rate of climb and angle of attack information with a two dimensional display h versus h compared to nominal, and in the other case, the basic panel plus an ILS indicator displaying a signal which the pilot was to minimize. It was predicted that with a quickened signal displayed on the ILS indicator that manual control system performance would be much improved. The ILS error signal was computed on the basis of an optimal response for the entire guidance and control loop using the Butterworth criterion. A number of approximations were made which were valid during the second and third stages of boost flight, and a set of gains was selected which would yield a Butterworth response, but only toward the end of third stage flight. In spite of the approximations involved, the pilot's control of the vehicle was greatly improved to the point that he could deliberately deviate from nominal, and then compensate with ease.

Quickened signals can be computed on the basis of a variety of system performance criteria and theoretically achieve optimal trajectories. The above approach could be improved by implementing time variable gains for the derivative terms summed on the ILS display. Optimal control theory gives promise of highly refined solutions. It can be predicted that the display of this kind of information will improve manual control system performance provided, of course, that the human operator is able to null the error indication. However, the display signal is usually derived on the basis of the pilot being a low-pass amplifier, and thus the pilot's task is ordinarily quite easy. It should be pointed out that if the pilot serves only as an amplifier in the control system, theoretically he can be by-passed. Fortunately, it is usually clear in practice as to the trade-offs involved with including this as a pilot mode, and the quickened mode may be viewed as another point for pilot insertion subject to the same considerations as other modes of pilot control.

V. MANNED BOOSTER GUIDANCE AND CONTROL: AN EVALUATION

A. Five Criteria for Evaluation

At the beginning of this report, five general criteria were suggested for the evaluation of piloted booster guidance and control systems. These were: stability, response efficiency, reliability, adaptability, and acceptability. With much of the data now at hand, it is possible to make qualitative judgments in each of these five areas. Hopefully, this will allow a general assessment of the current state of the art, and provide broad directions for future work.

1. Stability. Over a large number of simulated boosters with widely varying stable and unstable dynamics, it has been definitely shown that the skilled pilot can effectively and rapidly provide system stabilization. Specific stabilization limits are beginning to be defined, but generalizations at the present time are risky. One consistent finding is that rate stability augmentation is essential for a minimal manual control concept. With the exception of severe cross-coupling phenomena, the ability of the pilot to provide stabilization does not appear to be influenced as much by the vehicular dynamics as it does by his position in the control loop, his task loading, and display variables.

The evidence suggests that a pilot override stabilization function is a feasible design concept. If valid for a particular application, this could relieve automatic control requirements for some unusual stabilization conditions. In override, this does not mean, necessarily or even probably, that the pilot could re-establish an optimum flight path, but, at best, he could achieve orbital injection or, at worst, elicit better conditions for abort. These generalizations need much more empirical study, but the evidence suggests that investigations in this area would be fruitful.

2. Response efficiency. In literally hundreds of simulated full trajectory flights, skilled pilots have demonstrated repeatedly their ability to fly precision nominal trajectories from launch to orbital insertion. The problem at present lies in the specific terminal precision requirements. For all current manned space vehicles, terminal boost requirements are extremely (and, perhaps, unreasonably) stringent. Pilots have not been able to achieve consistent repeated terminal conditions within these limits. However, it may be that even the best automatic guidance and control systems will not be able to fulfill these standards either. It would be desirable to collect data from a given application comparing terminal performance distributions

for automatic and manual trajectory guidance and control. Some limited comparisons of this type have been made, but the data are not available in the open literature.

The question at this point in time is not if man can fly booster trajectories but rather the repeated precision with which he does so. It is to be hoped that, in future studies, larger numbers of pilots and many more trajectory runs will be made in each case. Feasibility demonstrations are no longer needed; large sample data are essential to show precision and variability of pilot response efficiency.

3. Reliability. The lack of these data make precise reliability estimates of pilot performance during boost impossible. Reliability may be defined within this context as the probability of repeated performance within a stated set of precision limits. Without large sample distribution data, a reliable probability figure cannot be estimated. Only one study has attempted such an estimate (ref. 19). With a very strict set of terminal value requirements, pilots achieved successful insertion only once out of every four trials. With improved displays, one out of two trajectory flights were successful. The reliability range was, therefore, 0.25 to 0.50 - not particularly impressive values.

It has been widely hypothesized that the pilot can improve automatic control system reliability by serving as an emergency backup system. As noted previously, there is strong evidence supporting this inference with respect to emergency stabilization. But there are not sufficient direct data to make this more than an inference. There have been no systematic studies where the pilot has accepted guidance and control responsibility at varying stages of booster flight and under differing emergency circumstances. Such data would be quite desirable, and, until available, pilot contribution to booster reliability under nonnominal, emergency, or abort conditions remains an unanswered problem. This is perhaps the most pressing data requirement in the area.

4. Adaptability. The simple fact that skilled pilots have demonstrated their guidance and control ability in a wide variety of simulated booster systems attests, once again, to the wide adaptability of the pilot as a guidance and control element. With respect to the three specific problems raised at the beginning of this paper, (a) there has as yet been no demonstration that he does achieve more precise trajectory flights, (b) there are strong indications that he would be effective as vernier backup (ref. 31), and (c) as just noted, his off-nominal and abort capabilities have not been explored.

5. Acceptability. None of the studies noted here have been concerned with the traditional handling qualities judgments with the exception of some limited data in the report of Holleman, Armstrong and Andrews (ref. 18). In general, however, what constitutes a range of acceptable handling qualities from the pilot standpoint remains an open question. In our experience, training has played a very large part in pilot acceptability particularly with marginal control conditions where, with increased training over extended periods, pilots are far more willing to accept a marginal mode. From a methodological standpoint, in future studies, pilot judgments about handling qualities should probably not be recorded until the pilots have had extensive training and familiarization.

B. Future Studies

Hopefully, it is now apparent that the problem of manual booster control is an exceptionally complex one. In the opinion of the writers, there is no more difficult and challenging piloting task in the entire area of manual control systems - with the possible exception of manual earth re-entry and landing. And, for the manual control specialist, it is an inherently fascinating problem. A long list of possible future research studies could be made easily; however, only four will be mentioned, representing our judgments as to the most critical problem areas.

(1) The problem of manual booster control was initiated from examination of a number of forthcoming large space boosters. The basic questions of response efficiency, reliability and adaptability are still open. One solution is to take a set of boosters (e.g., Titan III, Saturn C-5, Nova), simulate them as well as possible, and fly repeated nominal, off-nominal, and abort trajectory flights with a large sample of skilled pilots. This study would derive the normative data essential to valid and reliable quantitative information about response efficiency, reliability, and pilot adaptability. These data would provide a basis for rational design decisions for these boosters, and considerably reduce speculation and controversy.

(2) A concentrated effort is needed on the development of better display systems. With crude displays the pilots have flown remarkably well. Given the same quality input data, automatic systems would very probably compare very poorly with the manual modes. Better display systems can be developed, and they will help produce far better pilot performance.

(3) The basic approach in this paper has been not to compare "automatic" with "manual" control but rather to judge the relative contributions of manual and automatic functions, in combination, to the fundamental booster guidance and control requirements. The problem, then, is not one of discrete alternatives but rather function trade-offs. If this assumption is correct, trade-off analysis, with supporting empirical data, deserve a great deal more emphasis.

(4) Control system theory has yet to play a significant role in this area. It may be that the problem simply does warrant a major theoretical effort. To develop rigorous theory is to open the door wide to nonlinear control system theory. With the inclusion of man, the theoretical and mathematical barriers become staggering. A straight empirical approach will generate all the information necessary to the specific design problems. But one is tempted to speculate that the creation of valid and adequate theory and analytic tools for this area could result in a set of methods appropriate for any man-machine guidance and control system.

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